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Hydraulic Compression of Shaft Backfill at the Backfill/Rock Interface

Report No 86-283-K

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ABSTRACT

Based on theoretical considerations, this report shows that the horizontal pressure acting on the backfill/rock interface of a shaft can be quite small due to the shearing resistance developed between the compressible backfill and the rock surface. A laboratory program was then carried out to measure the horizontal pressures in two model shafts and the experimental data were compared with theoretical results. In addition, hydraulic compression experiments were performed on backfill specimens compacted in an apparatus specially designed for these tests. The practical implications of the laboratory findings on the design of shaft backfills are discussed.

job	file	date	report no.
43-302-061	843.2	November 28, 1986	86-283-K

91602
new 82-10

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HYDRAULIC COMPRESSION OF SHAFT BACKFILL AT THE BACKFILL/ROCK INTERFACE

1.0 INTRODUCTION

In the proposed Canadian design of an underground repository for radioactive fuel wastes, adequate isolation of the radionuclides from the geosphere to the biosphere must be ensured for a very long period of time. To meet this stringent requirement, the shafts, drifts, boreholes and disposal vaults must be adequately sealed in such a way that they do not constitute easy pathways for the transport of radionuclides/1/. It is assumed that in the repository design, the shafts would be backfilled with a compacted clay soil mixed with sand or crushed granite. Because of the shearing resistance developed at the backfill/rock interface of the shaft, the vertical soil pressure is greatly reduced. As a result, the horizontal pressure becomes quite small. The reduction of the horizontal pressure at the shaft backfill/rock interface coupled with a large hydraulic pressure due to recharging groundwater may develop a gap at the interface, potentially a critical groundwater flow path.

This report deals with the horizontal pressure acting at a vertical shaft backfill/rock wall interface and the behaviour of the backfill under the influence of water pressure in the horizontal direction at the same interface.

This report first presents a theoretical expression for the computation of the vertical and horizontal pressures in a soil column in a shaft. Then it discusses the results of laboratory measurements in model shafts and observations in hydraulic compression experiments on compacted backfill specimens.

2.0 BACKFILL ROCK INTERFACE

According to the classical theories of arching/2/, the vertical pressure in the backfill along the depth of a shaft increases less rapidly than the weight of the backfill and approaches asymptotically a finite value due to the shearing resistance developed between the backfill and the shaft wall. A simplified analytical solution for the vertical pressure distribution can be derived by rewriting Janssen equations in terms of effective pressures and using the following assumptions/3/:

(1) the shaft wall is rigid,

(2) vertical pressures are uniform in horizontal planes,

(3) the ratio (ko) of effective horizontal to vertical pressures is constant with depth ($ko = \sigma'_h/\sigma'_v$),

(4) the backfill/rock interface is the surface of sliding and the vertical pressure in the yielding part of backfill is equal to the difference between the weight of backfill above the section and the shear resistance (S_b) along the interface. If S_b does not fully develop to the shearing strength along the interface, then

$$S_b = \frac{\tau}{F} = (c'_a + \sigma'_h \tan\delta)/F$$

where: τ = shear strength

c'_a = effective cohesion of backfill

σ'_h = effective horizontal pressure

δ = frictional angle

F = shearing mobilization factor

$$\sigma'_h = P_{s(h)} + (\sigma_h - u)$$

where: $P_{s(h)}$ = horizontal component of swelling pressure

σ_h = total horizontal pressure

u = pore pressure

It is assumed that backfill construction will proceed without consolidation and the pore pressure, u, will be related to σ_v (vertical pressure). Therefore, assuming that the rate of backfilling is rapid, the "end of construction" pore pressure is as follows:

$$u = u_o + \bar{B}\sigma_v$$

where: u_o = pore pressure immediately after backfill placement

$\bar{B}\sigma_v$ = change in pore pressure accompanying a change in vertical pressure from 0 to σ_v

$$\therefore (\sigma_h - u) = k_o(\sigma_v - u) = k_o(\sigma_v - u_o - \bar{B}\sigma_v)$$

$$= k_o(\sigma_v(1-\bar{B}) - u_o)$$

(5) changes in the vertical component of swelling pressure is neglected and the horizontal component of swelling pressure $P_{s(h)}$ is assumed constant with depth,

(6) the backfill is uniform in density, and

(7) lateral pressure due to compaction of the backfill is considered negligible.

Figure 1 represents a column of backfill in a circular shaft, of radius a, which is settling under its own weight. The condition that the sum of the vertical pressure components acting on the slice must be equal to zero, can be expressed as follows:

$$\pi a^2 \gamma dz = \pi a^2 (\sigma_v' + d\sigma_v') - \pi a^2 \sigma_v' +$$

$$2\pi a \left\{ \frac{P_{s(h)} \tan\delta + (c_a' + k_o(\sigma_v(1-\bar{B}) - u_o)\tan\delta)}{F} \right\} dz \qquad (1)$$

$$\text{or} \quad \frac{d\sigma_v'}{dz} = \gamma - \frac{2}{a} \left\{ \frac{P_{s(h)} \tan\delta + [k_o(\sigma_v(1-\bar{B}) - u_o)\tan\delta + c_a']}{F} \right\} \qquad (2)$$

where: $\tan\delta$ = frictional coefficient between backfill and shaft rock-wall surface
c'_a = the adhesion at the interfacial zone
γ = unit weight of backfill
$P_{s(h)}$ = horizontal component of swelling pressure
k_o = earth pressure coefficient at rest
$\bar{B}$ = pore pressure coefficient
F = shearing mobilization factor

By integrating this equation with boundary conditions that $\sigma_v = 0$ when $z = 0$

$$\sigma'_v = \frac{1}{A}\left[\gamma - \frac{2}{Fa}\left(c'_a + P_{s(h)}\tan\delta - u_o k_o \tan\delta\right)\right](1-e^{-Az}) - u_o \qquad (3)$$

where:

$$A = \frac{[2k_o \tan\delta(1-\bar{B})]}{Fa}$$

$$\sigma'_h = \sigma'_v \cdot k_o \qquad (4)$$

3.0 HORIZONTAL PRESSURE MEASUREMENTS IN BACKFILLED SHAFT MODELS

To study the horizontal pressure distribution in the backfill placed in a shaft, a laboratory testing program was carried out to measure the horizontal pressures in two shaft models. The collected experimental results were then used to compare with the calculated results using the equations developed in the previous section of the report.

The dimensions of the two model shafts are shown in Figure 2. The first of the two shaft models was constructed of a 152.4 mm diameter stainless steel pipe and the second was constructed of a PVC pipe 304.8 mm in diameter. Figure 3 is a photograph of the 304.8 mm diameter model. Three pressure transducers were used to measure the horizontal pressure exerted by the backfill on the inner wall surface of the pipe. The transducers were each calibrated using known heads of water in a container. Two types of backfills were used in the experimental program: an

air dry silica sand and an illite clay (sealbond[1]) mixed with crushed granite. Table 1 is a summary of the tests performed and the various types of backfill materials used in the experiments.

In test No. 1, silica sand was placed loosely in the 152.4 mm diameter model. The sand was a dry material and therefore no pore water pressure was generated during the placement of the backfill material. Furthermore, because the material was loosely placed inside the model, a very small horizontal pressure was induced by the placement of the material.

Figure 4 shows the horizontal pressure measurements of the silica sand exerting on the inside wall of the 152.4 mm Ø model. Three pressure transducers were used to measure the backfill pressure and they are identified as the "top", "middle", and "bottom" transducers. The measured horizontal pressures were found to be small. In Figure 5, the variation of the measured horizontal pressure with depth is compared with the theoretical pressure distribution. A range of reasonable values for k_o and δ were assumed for loose sand in the calculations. Figure 6 and Figure 7 also show results obtained in the 304.8 mm diameter shaft model for the same silica sand. The following conclusions may be drawn from the results in Figures 4 to 7:

(1) The horizontal pressures are smaller in the 152.4 mm diameter shaft model than in the 304.8 mm shaft model because of the larger shearing resistance developed between the sand and the smaller diameter shaft.

(2) The horizontal pressure increase with depth is much smaller than that estimated for the "no soil arching" case (ie, no shearing resistance developed between the soil and the shaft).

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1. Sealbond is crushed shale material produced by a brick manufacturing company in Toronto.

(3) The experimental observations compare favourably with predictions.

The above tests were repeated with Sealbond (clayey soil) material. Figure 8 shows the variation of the horizontal pressures with time in the backfill in the 152.4 mm diameter model. Initially, the horizontal pressure was higher because of the excess pore water in the backfill induced by the placement of the clayey soil backfill in the model. In about ten days, the horizontal pressure became fairly constant. Subsequent small variations in the pressure measurements may have resulted from rearrangement of soil particles during consolidation of the backfill. Figure 9 shows the comparison between the measured horizontal pressures with the theoretical results. The soil parameters (c'_a and δ) were obtained from direct shear tests on Sealbond sliding against a steel plate surface. The assumed values of k_o and F used in Equations (3) and (4) were considered reasonable for the test conditions. The following observations can be made from the results presented in Figure 9:

(1) The measured pressures were the "total pressure" (sum of interparticle pressure and pore water pressure) and their values were much smaller than the horizontal pressures estimated for the "no soil arching" case (ie, no shear resistance developed between the soil backfill and the shaft surface).

(2) The comparison between the measured and the theoretical pressures is not as good as anticipated. However, if a small value of pore water pressure (not measured in this experiment) is subtracted from the measured pressures, the experimental and the theoretical results would compare more closely.

Figure 10 shows the horizontal pressures measured in the 304.8 mm diameter shaft model backfilled with Sealbond. After the placement of the backfill, the pore water pressure was high and it decreased quickly with time. The pressures became nearly constant after 14 days. In Figure 11, a comparison is made of the experimental and theoretical results. The soil parameters (c'_a and δ) were obtained by shearing a Sealbond specimen on a PVC plate. Again, the pressure measurements show that horizontal pressures are substantially smaller than those in the "no soil arching" case.

4.0 HYDRAULIC COMPRESSION EXPERIMENTS

The experimental study described in the previous section has shown that with the shearing resistance developed between the backfill and the shaft model, the vertical and horizontal pressures due to the self weight of the backfill is greatly reduced. The results of these experiments suggest that the contact pressure between the backfill and the shaft rock could be quite small. As a result, during the groundwater recharging phase, the large hydraulic pressure at the backfill/rock interface could cause undesirable compression of the backfill and hence the potential development of a gap at the interface.

In order to investigate the lateral compression of compacted clay-based specimens by hydraulic pressure, the following experiments were performed.

An apparatus was designed and constructed as shown in Figures 12 and 13. The cell consists of a stainless steel outer ring, an inner porous bronze liner and the top and bottom steel plates. The outer ring is 76.2 mm in height, 219 mm in outside diameter and 7.9 mm in wall thickness. The inner bronze porous liner is of 203.2 mm outside diameter and 29.4 mm thickness, and fits tightly within the outer ring. Two holes are drilled in the outer ring to let water in and to displace trapped air. The porous liner was used to distribute water pressure on the sides of the test specimen. A total of two cells were manufactured. In order to measure the contact pressure at the specimen/liner interface, the pressure transducers are mounted with their sensing diaphragm flush with the inner surface of the porous liner (Figure 14). A pressure transducer is also installed on the top steel plate to measure the pressure at the interface between the top plate and the specimen. On the bottom plate, provision is made for applying pressure through an opening to the circular porous plate and to the specimen. A latex membrane is placed between the specimen and the circular porous plate to prevent water leakage from the specimen. (The feature of applying vertical pressure to the bottom side of the specimen was not used in the hydraulic compression tests reported in this report.) In the other cell, only one transducer is used to measure the contact pressure at the specimen/porous liner interface and there is no provision to apply vertical pressure to the specimen at the bottom surface.

Before a specimen was placed in the porous liner, attempts were made to saturate the liner by boiling it in a chamber. Then the liner was fitted into the outer steel ring and the backfill material was compacted in it to a pre-determined density. The

specimen was compacted to a height slightly greater than that of the porous liner so that good contact between the top steel plate and the specimen could be ensured.

The main purpose of this experimental program was to demonstrate, under laboratory conditions, whether or not a gap would develop between a compacted soil specimen and the porous liner at a certain hydraulic pressure. Three groups of backfill specimens were used:

(i) calcium (Pembina) bentonite mixed with crushed granite compacted to a dry density of about 1500 kg/m^3;

(ii) same backfill mix as (i) compacted to a dry density ranging from 1570 to 1770 kg/m^3; and

(iii) calcium (Pembina) bentonite and sodium (Avonlea) bentonite mixed with crushed granite compacted to a dry density from 1570 to 1630 kg/m^3.

Details of the mixes are summarized in Table 2.

After the backfill was compacted in the cell, a small vertical pressure on the specimen was induced by tightening the top plate on the specimen. The resultant horizontal backfill pressure on the liner was also quite small (eg, generally less than 50 kPa).

Initially, a water pressure of about 50 kPa was applied to the specimen for about 1 day. Then a much larger water pressure (up to 1400 kPa) was applied to the specimen for a duration ranging from 1 day to several weeks, during which time the horizontal and the vertical pressures were monitored. Under the influence of the applied water pressure, water would flow into the compacted specimen and radial compression of the specimen might occur due to volume decrease in the pores which were not completely filled with water and also due to air bubbles dissolving in the water. As long as the backfill was in contact with the liner, the transducer would measure the total pressure equal to the pressure of the soil particles pushing the liner, plus the water pressure. However, if there was a gap developed at the backfill/liner interface due to lateral compression of the specimen, the water pressure in the gap would be the same as the water - pressure in the liner (ie, the applied water pressure). The transducer would then measure a pressure equal to the applied water pressure.

Table 2 summarizes the pertinent data of the laboratory hydraulic compression tests. The results illustrate the effect

of backfill specimen density, which is related to the degree of compaction, the magnitude of the applied water pressure and the composition of the specimens. When the specimens were not well compacted, (eg, dry density ~1500 kg/m^3) a gap was developed at the specimen/liner interface. However, when the same backfill was compacted to a higher dry density (e.g. 1770 kg/m^3), no gap was developed when a water pressure of about 1400 kPa was used to compress the specimen. Also, when a 10% sodium bentonite was mixed with the calcium bentonite and crushed granite, no gap was present at the specimen/liner boundary.

It is believed that these laboratory findings will have significant implications in the design of the backfill in a vertical shaft for sealing purposes.

5.0 SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

Based on the laboratory shaft model experiments, it may be inferred that, if a clay-based material is used to backfill a vertical shaft, the horizontal pressure at the backfill/rock interface may be significantly reduced because of the shearing resistant developed at that interface. This should be taken into consideration in the design of the shaft backfill when it is subjected to the recharging groundwater pressure.

The laboratory hydraulic compression experiments conducted in this project have demonstrated that a poorly-compacted clay-based backfill specimen could easily be compressed hydraulically to the extent that a gap would develop between the specimen/porous liner interface. However, when the same backfill specimen was compacted to a higher density or when a certain amount of sodium bentonite (swelling clay) was added to the mix and compacted to a certain minimum density, no gap was observed at the specimen/porous liner interface for a maximum applied water pressure of about 1400 kPa.

These laboratory data would serve to draw the attention of shaft backfill designers to the effect of recharging groundwater pressure on the compressible shaft backfill, such as a clay-based material.

In general, the behaviour of a shaft backfill under the influence of the groundwater pressure at the repository site depends on many factors, such as (i) the difference between the water pressure in the backfill and the groundwater pressure at the backfill/rock interface; (ii) the hydraulic conductivity of the initially unsaturated backfill; (iii) the compressibility of the backfill, and; (iv) the initial contact pressure at the

backfill/rock interface. When the repository site conditions are better known and when the backfill mix is finalized, the behaviour of the backfill may be predicted by performing laboratory tests under simulated long-term field conditions at the backfill/rock wall boundary. Furthermore, a mathematical model may be developed to study the various factors affecting the shaft backfill under hydraulic compression in the field.

Based on the limited experience gained in this experimental study, the following suggestions for the design of a clay-based backfill may be made:

(1) The shaft backfill should be compacted to a certain minimum density, which can be decided upon by performing hydraulic compression tests using an apparatus similar to the one used in this project.

(2) It is beneficial to increase the vertical pressure in the backfill column and hence the horizontal pressure at the backfill/rock interface in a vertical shaft. If concrete bulkheads are used to separate the backfill column, highly compacted sodium bentonite may be placed between the bulkhead and the backfill to increase the vertical pressure and hence the lateral pressure at the backfill/rock interface.

(3) A certain quantity of swelling clay (eg, sodium bentonite) should be mixed with the backfill to create sufficient pressure at the backfill/rock interface. Alternatively, a certain thickness of swelling clay may be placed between the backfill and the shaft rock. This sandwiched clay layer should expand sufficiently to prevent the potential development of a gap at the rock interface.

ACKNOWLEDGEMENTS

The writers would like to thank the following staff members of the Civil Research Department for their assistance in this study: Mesrs. Bob Rankin, Mike Grills, Don Fraser and Bob Watts.

The writers also benefitted from discussions with Mr. Mori Mortazavi, formerly of Ontario Hydro, and Professor Cam Kenney of the University of Toronto.

The project was funded partially by the Nuclear Materials Management Department of Ontario Hydro.

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REFERENCES

(1) LOPEZ, R.S., S.C.H. CHEUNG and D.A. DIXON, "The Canadian Program for Sealing Underground Nuclear Fu[illegible] Waste Vaults," Canadian Geotechnical Journal, Vol. 21, No. 3, pp 593-596, 1984.

(2) TERZAGHI, K., Theoretical Soil Mechanics, John Wiley and Sons, Chapter 5, 1962.

(3) MORTAZAVI, M.H.S., H.T. CHAN, and H.S. RADHAKRISHNA, "Design Considerations for Sealing the Shafts of a Nuclear Fuel Waste Disposal Vault," Ontario Hydro Research Division Report No. 85-13-K, 1985.

TABLE 1: BACKFILLS USED IN THE MODEL SHAFT EXPERIMENTS

Test	Model Shaft	Backfill		
		Material	Placement Method	Pore Water Pressure
1	152.4 mm Ø steel pipe	Dry silica sand, bulk density = 1575 kg/m^3	Material poured slowly in the pipe	No pore water pressure generated during placement of material.
2	304.8 mm Ø PVC pipe	Dry silica sand, bulk density = 1575 kg/m^3	Material poured slowly in the pipe	No pore water pressure generated during placement of material.
3	152.4 mm Ø steel pipe	Sealbond w = 25% bulk density = 1935 kg/m^3	Material loosely placed in the pipe	Excessive pore water pressure generated during placement of material and it dissipated in a few days.
4	304.8 mm Ø PVC pipe	Sealbond w = 25% bulk density = 1911 kg/m^3	Material loosely placed in the pipe	Excessive pore water pressure generated during placement of material and it dissipated in a few days.

TABLE 2

PERTINENT DATA FROM HYDRAULIC COMPRESSION TESTS

Specimen	Density (kg/m³) Bulk	Density (kg/m³) Dry	Water Content (%) Initial	Water Content (%) Final	Max Applied Water Pressure (kPa)	Number of Days Pressure Applied	Measured Pressure (kPa) Horizontal Location 1	Measured Pressure (kPa) Horizontal Location 2	Measured Pressure (kPa) Vertical	Comments
75% Crusher Granite (C.G) 25% Calcium Bentonite (C.B)	1760	1530	15.0	18.7 (top) 18.5 (middle) 15.6 (bottom)	100	2	102	100	102	-Measured pressures = applied water pressure, indicating a gap present at specimen/liner interface and specimen/top plate interface.
75% C.G. 25% C.B.	1749	1517	15.3	20.4 (top) 19.2 (middle) 28.7 (bottom)	596	3	602	595	618	-Same comments as above.
75% C.G. 25% C.B.	1768	1511	17.0	22.0 (top) 22.1 (middle) 22.7 (bottom)	600	2	605		600	-Same comments as above.
75% C.G. 25% C.B.	1845	1605	15.0	Avg. 21.3	696	18	739		291	-Measured horizontal pressure greater than the applied water pressure, indicating the specimen was in contact with the liner. -Measured vertical pressure seemed too low. Probably due to the upper plate warping slightly upward at the centre.
75% C.G. 25% C.B.	1900	1652	15.0	19.0 (top) 20.6 (middle) 24.5 (bottom)	600	2	651	609	618	-Horizontal 2 pressure = the applied water pressure, indicating a gap present at specimen/liner interface at that transducer location. Contact between specimen/liner seemed good at other transducer location. Difference could be due to uneven compaction of specimen.
75% C.G. 25% C.B.	1858	1572	18.2	Avg. 18.2	1208	28	1201	1167	444	-Measured horizontal pressure = applied water pressure, indicating a gap at specimen/liner interface. -Measured vertical pressure seemed too low. Probably due to slight warping of the upper steel plate.
75% C.G. 25% C.B.	2040	1774	15.0	20.3 (top) 18.9 (middle) 21.8 (bottom)	1398	56	1641	1873	1464	-No gap present between specimen/liner interface. -Measured horizontal pressure not equal, probably due to uneven compaction of specimen.
75% C.G. 20% C.B. 5% Sodium Bentonite (S.B.)	1872	1628	15.0	26.1 (top) 25.2 (middle) 25.5 (bottom)	1420	43	1414		990	-Measured horizontal pressure = applied water pressure, indicating a gap present at specimen/liner interface. The 5% sodium bentonite was not effective in preventing the gap development. -Vertical pressure seemed too low, probably due to slight warping of the upper plate.
75% C.G. 15% C.B. 10% S.B	1858	1572	18.2	24.6 (top) 25.4 (middle) 25.4 (bottom)	1390	37	1851		1481	-No gap was present at specimen/liner interface mainly because of the addition of sodium bentonite.

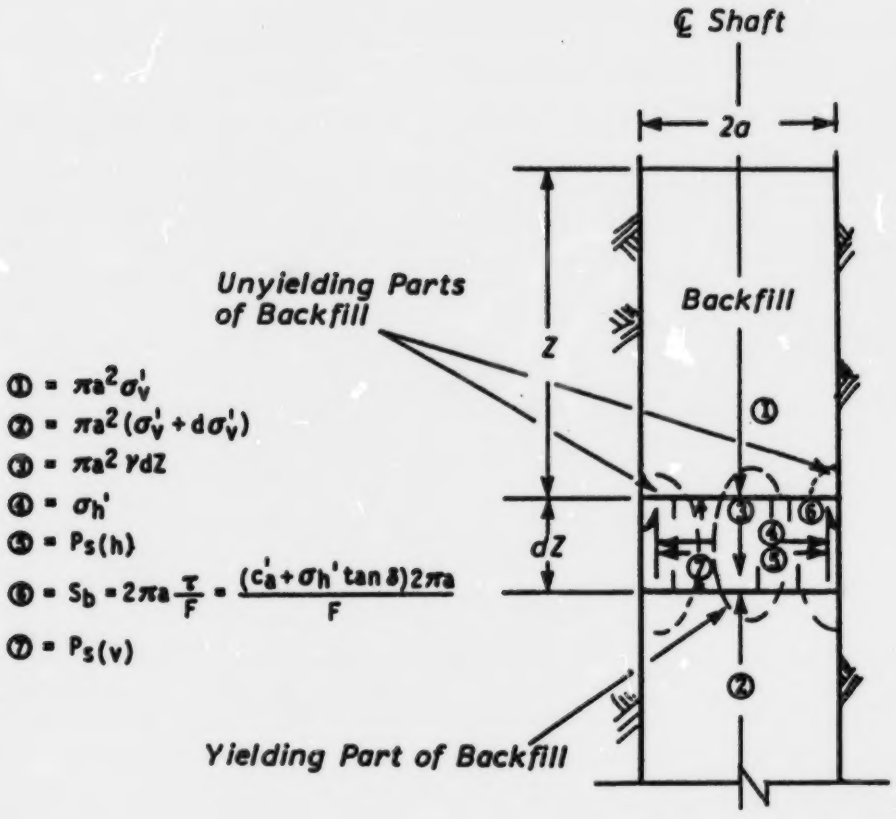

FIGURE 1
PRESSURES IN A BACKFILL SECTION IN A SHAFT

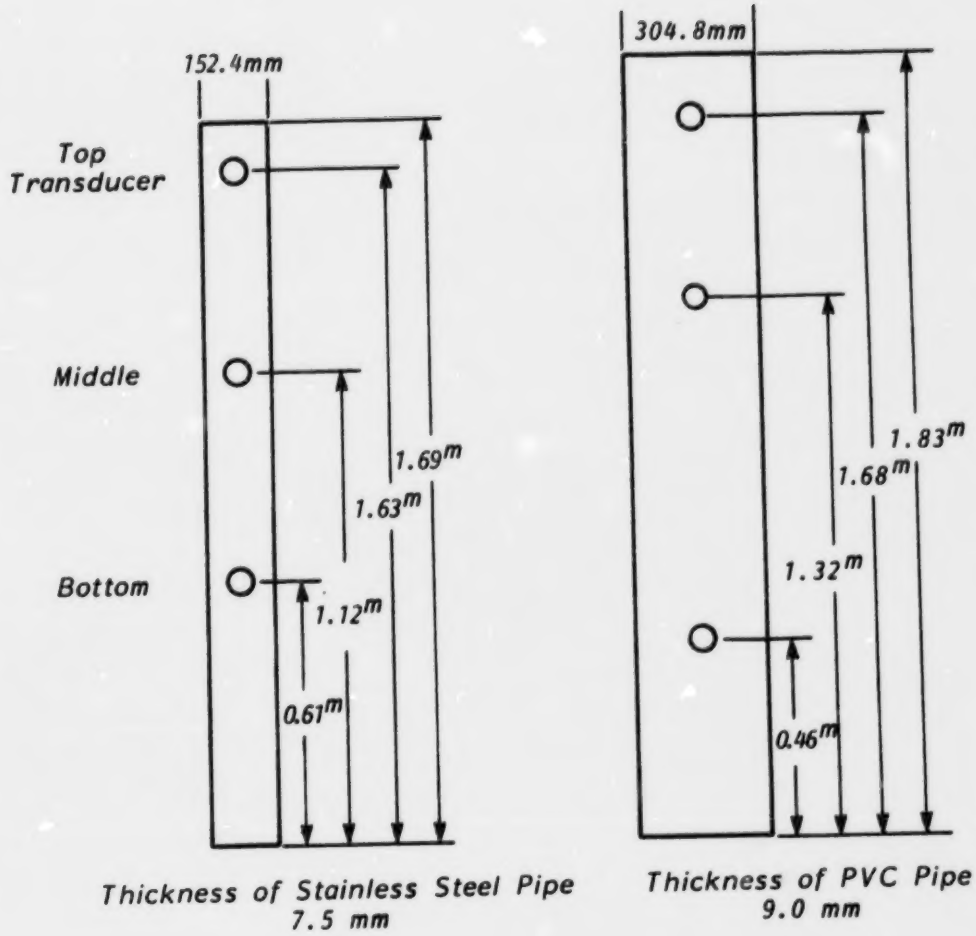

FIGURE 2

DIMENSIONS OF TWO CIRCULAR MODEL SHAFTS WITH LOCATIONS OF TRANSDUCERS SHOWN

FIGURE 3

A SHAFT MODEL CONSTRUCTED OF
PVC PIPE 304.8 mm IN DIAMETER

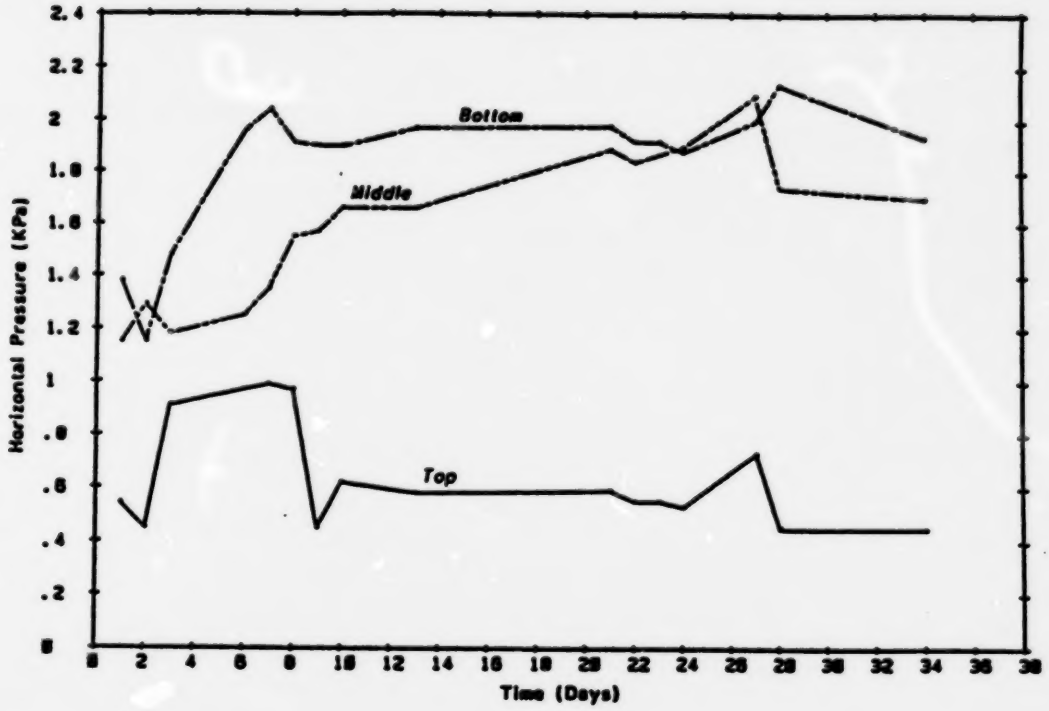

FIGURE 4

HORIZONTAL BACKFILL PRESSURE VARIATIONS WITH TIME.
DIAMETER OF MODEL SHAFT = 152.4 mm.
BULK DENSITY OF DRY SILICA SAND (BACKFILL) = 1575 kg/m^3

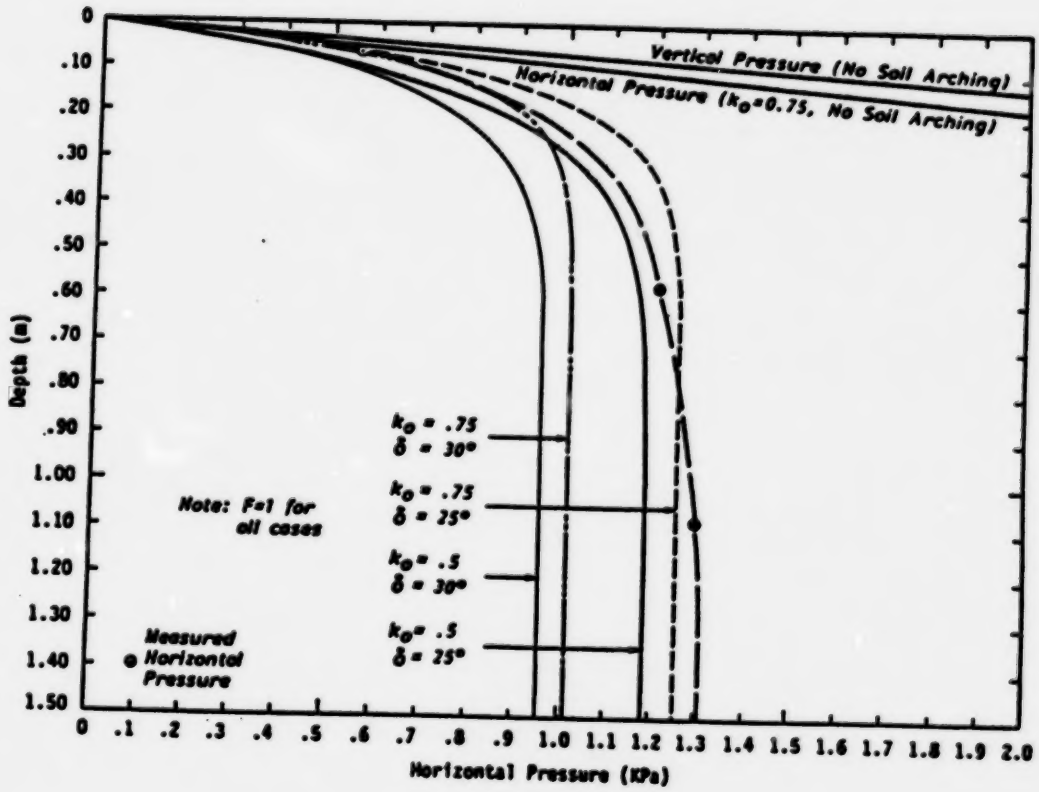

FIGURE 5

COMPARISON OF MEASURED BACKFILL HORIZONTAL PRESSURES IN THE 152.4 mm ϕ MODEL SHAFT WITH CALCULATED RESULTS. BULK DENSITY OF DRY SILICA SAND (BACKFILL) = 1575 kg/m^3

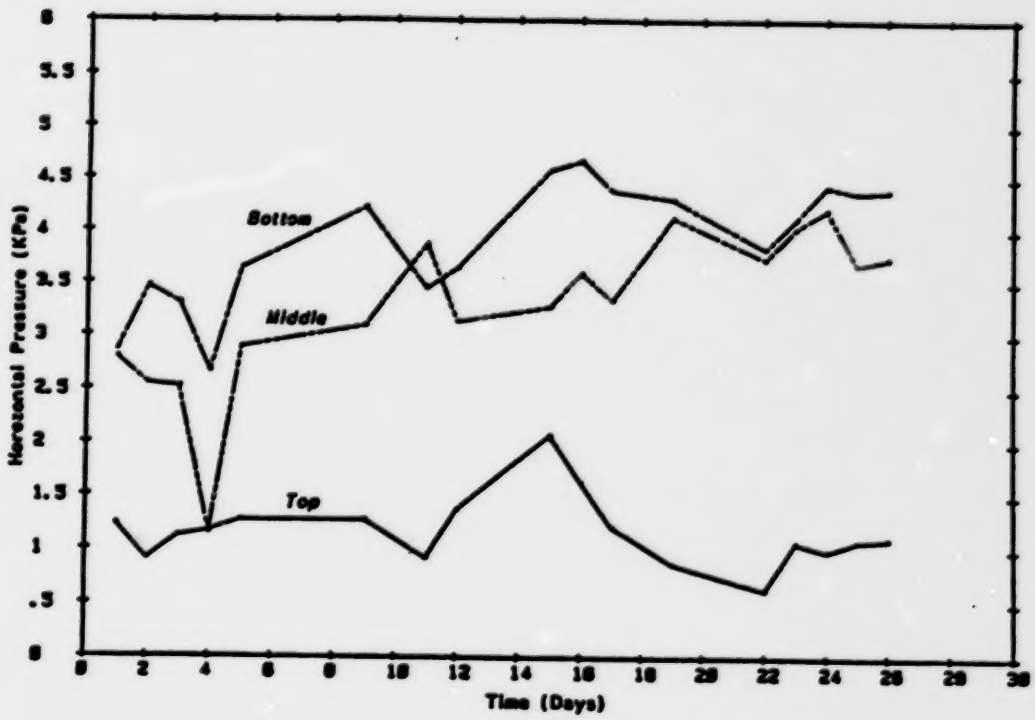

FIGURE 6

HORIZONTAL BACKFILL PRESSURE VARIATIONS WITH TIME.
DIAMETER OF MODEL SHAFT = 304.8 mm.
BULK DENSITY OF DRY SILICA SAND (BACKFILL) = 1575 kg/m^3

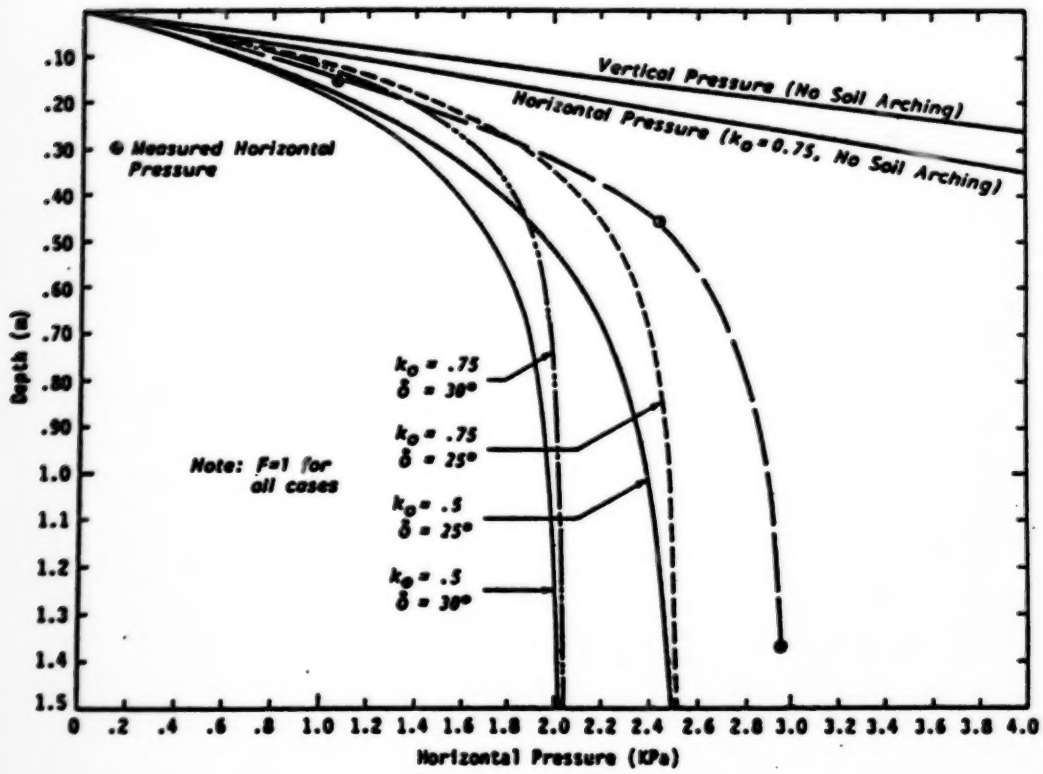

FIGURE 7

COMPARISON OF MEASURED BACKFILL HORIZONTAL PRESSURES IN THE 304.8 mm ϕ MODEL SHAFT WITH CALCULATED RESULTS. BULK DENSITY OF DRY SILICA SAND (BACKFILL) = 1575 kg/m^3

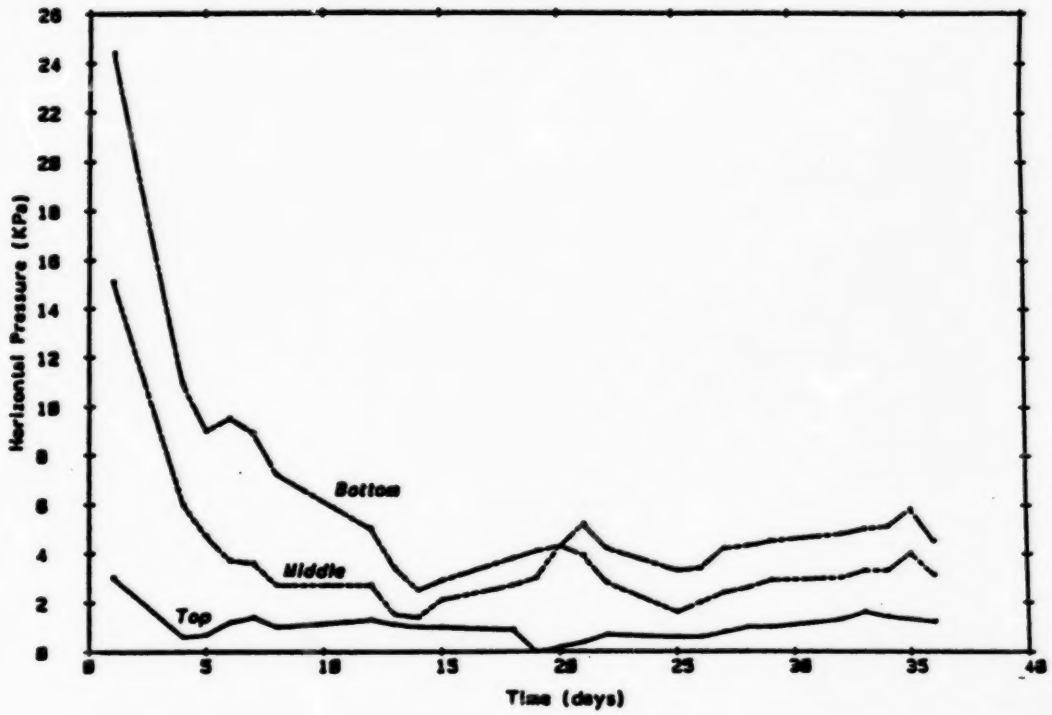

FIGURE 8

HORIZONTAL BACKFILL PRESSURE VARIATIONS WITH TIME.
DIAMETER OF MODEL SHAFT = 152.4 mm.
BULK DENSITY OF SEALBOND (BACKFILL) = 1935 kg/m^3
AT 25% WATER CONTENT.

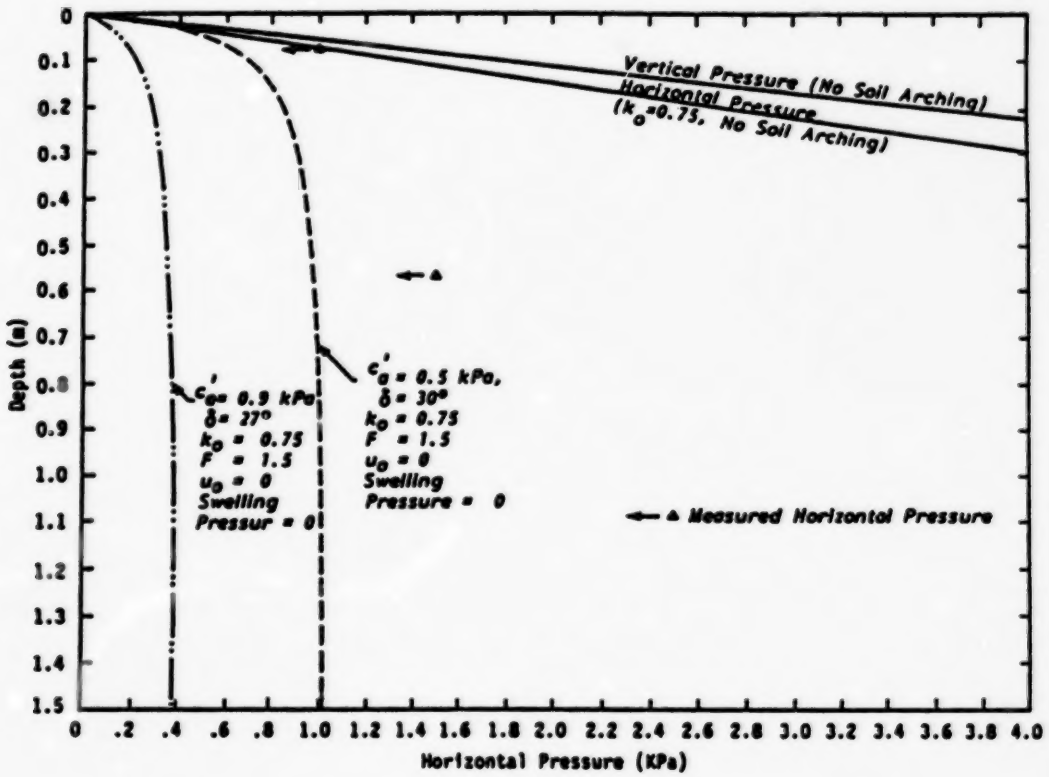

FIGURE 9

COMPARISON OF MEASURED BACKFILL HORIZONTAL PRESSURES IN THE 152.4 mm ϕ MODEL WITH CALCULATED RESULTS. BULK DENSITY OF SEALBOND (BACKFILL) = 1935 kg/m^3 AT 25% WATER CONTENT.

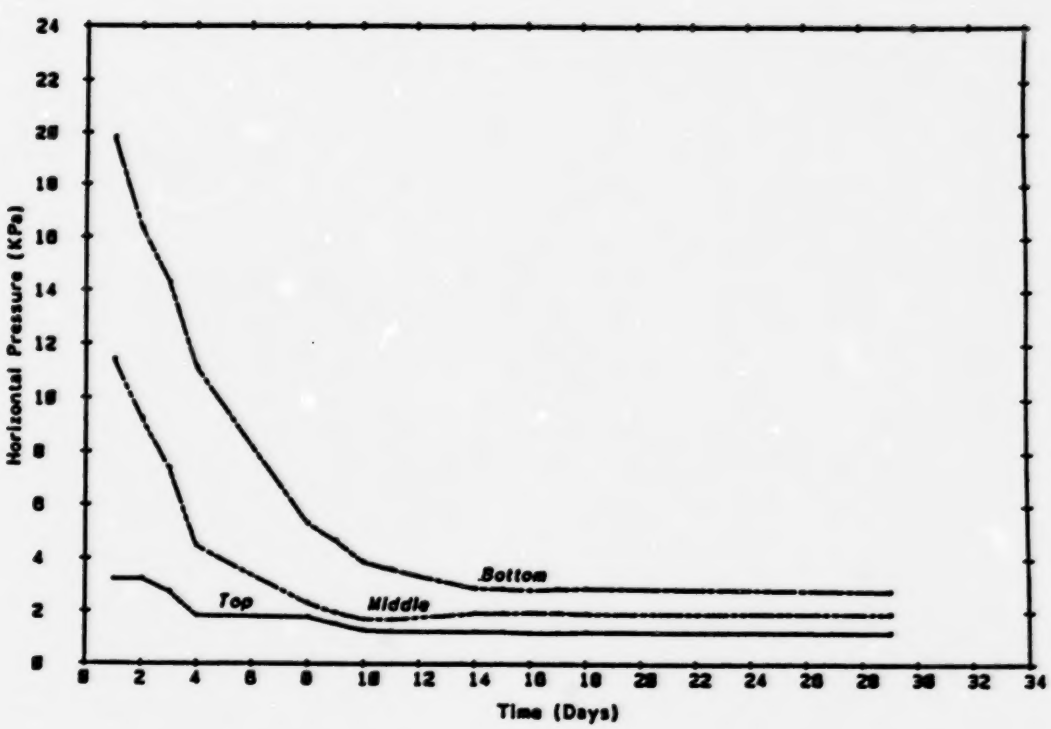

FIGURE 10

HORIZONTAL BACKFILL PRESSURE VARIATIONS WITH TIME.
DIAMETER OF MODEL SHAFT = 304.8 mm.
BULK DENSITY OF SEALBOND (BACKFILL) = 1911 kg/m^3
AT 25% WATER CONTENT.

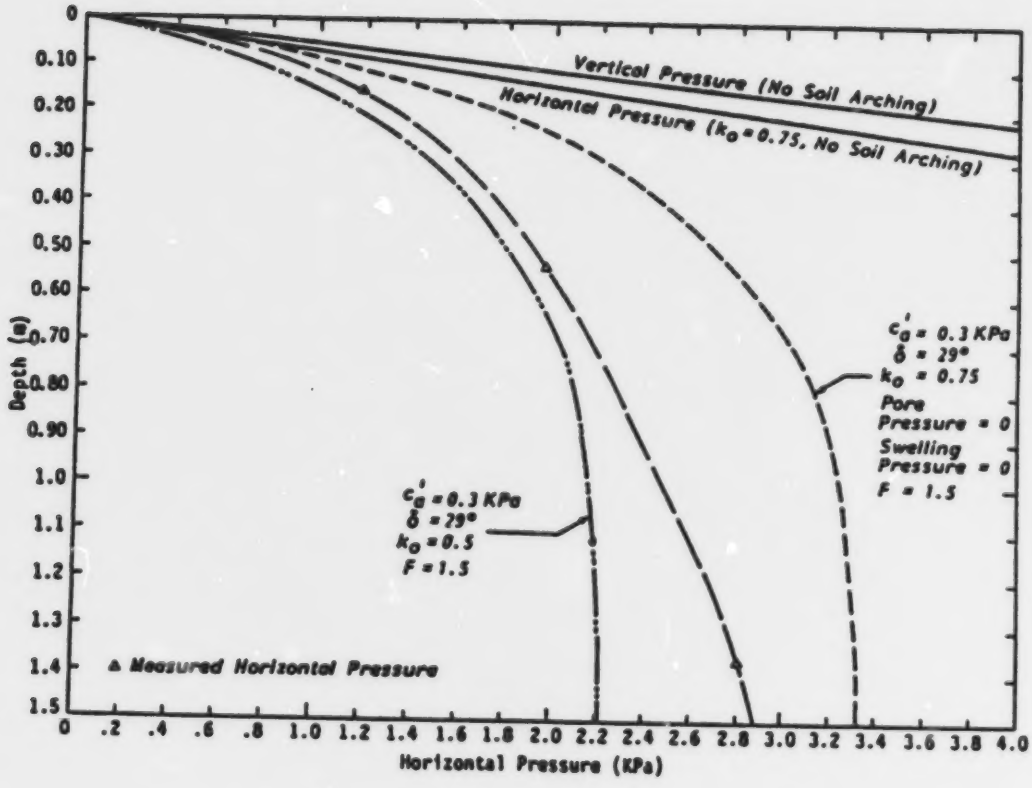

FIGURE 11

COMPARISON OF MEASURED BACKFILL HORIZONTAL PRESSURES IN THE 304.8 mm ϕ MODEL SHAFT WITH CALCULATED RESULTS. BULK DENSITY OF SEALBOND (BACKFILL) = 1911 kg/m^3 AT 25% WATER CONTENT.

FIGURE 12

VARIOUS PARTS OF THE CELL USED
FOR HYDRAULIC COMPRESSION TESTS

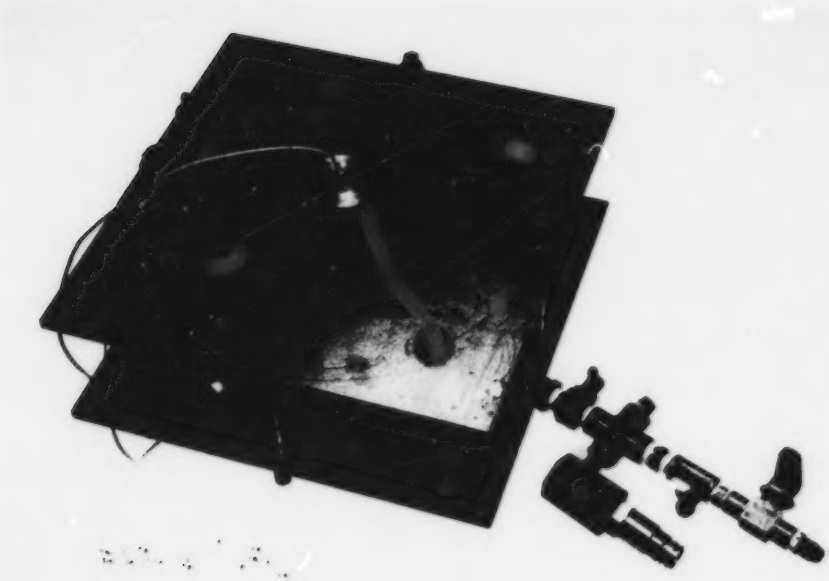

FIGURE 13
HYDRAULIC COMPRESSION CELL

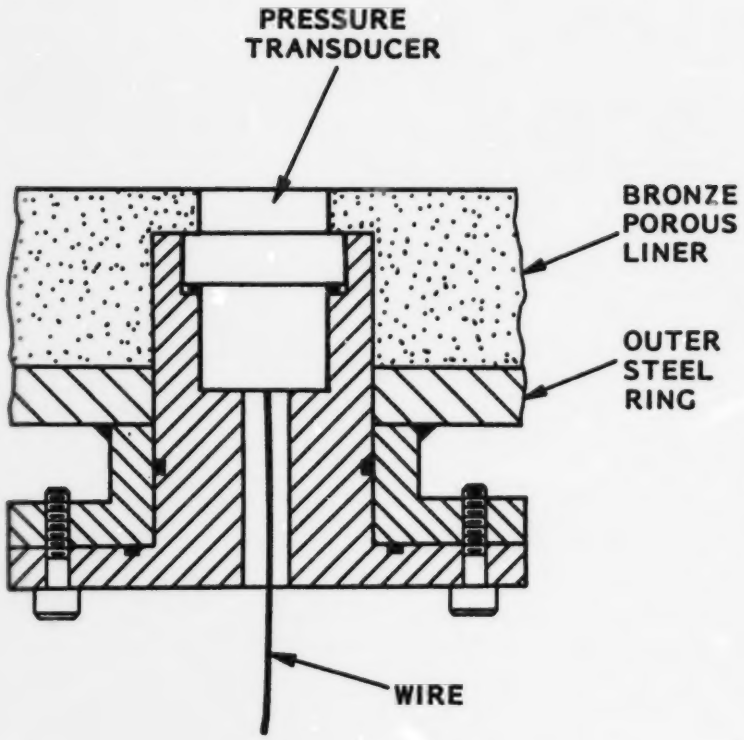

FIGURE 14

PRESSURE TRANSDUCER DIAPHRAGM FLUSH WITH
THE INNER SURFACE OF THE POROUS LINER
(Ø OF DIAPHRAGM = 19 mm)